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Abstract. During the period from December 1963 to April 1964, a large number of combined Faraday polarization and Doppler frequency measurements were made on lunar radar echoes at Stanford, California. The results of the measurements taken while the moon was in the anti-solar quadrant show a large spatial variation of the electron content beyond the ionosphere. A first-order model of the earth's magnetospheric wake is deduced, having the following characteristics: (1) the electron density inside the wake is about 200 cm^{-3} greater than the solar wind electron density; (2) the wake extends at least to the orbit of the moon; and (3) the wake intersects the lunar orbit at about 120° from the earth-sun line.

Author

Introduction. Since the first lunar radar echoes were made in 1946 [De Witt and Stodola, 1949], considerable effort has centered around determining the electron content of the ionosphere by measuring the Faraday polarization of the returned echoes [Browne et al, 1956]. A two-frequency Faraday polarization method was first introduced by Evans [1957] to measure the total electron content in the ionosphere. Subsequently, the two-frequency Faraday polarization method was extensively used by Evans and Taylor [1961] at Jodrell Bank.

Recently, another technique, based on dispersive Doppler effects, was used [Howard et al, 1964a] to find the rate of change of electron content along the entire lunar radar path. A combined Faraday and Doppler technique was first employed for the 20 July 1963 solar eclipse [Howard et al, 1964b].

From December 1963 to April 1964 daily measurements were made of the Faraday polarization and the dispersive Doppler frequency of dual-frequency radar echoes from the moon. This paper is a preliminary report on the analysis of the results obtained during the nighttime hours, when the moon was in directions opposite the sun. They suggest a rather large electron density inside the earth's magnetospheric wake, and an extension of the wake at least to the orbit of the moon. The electron density inside the wake appears to be about 200 cm^{-3} greater than in the solar wind region, and the width of the wake is approximately 100 earth radii at the lunar orbit. Recently, Howard et al [1965] made dual-frequency, group-path measurements of lunar radar echoes to determine the total columnar electron content between the earth and the moon. The results of these measurements complement the combined Faraday polarization and Doppler measurements reported here.

During this experiment the moon made more than five revolutions around the earth. Figure 1 represents the plane of the lunar orbit, looking from the north celestial pole. There are several different regions inside the lunar orbit, characterized by their different magnetic fields, high- and low-energy electron densities, and plasma

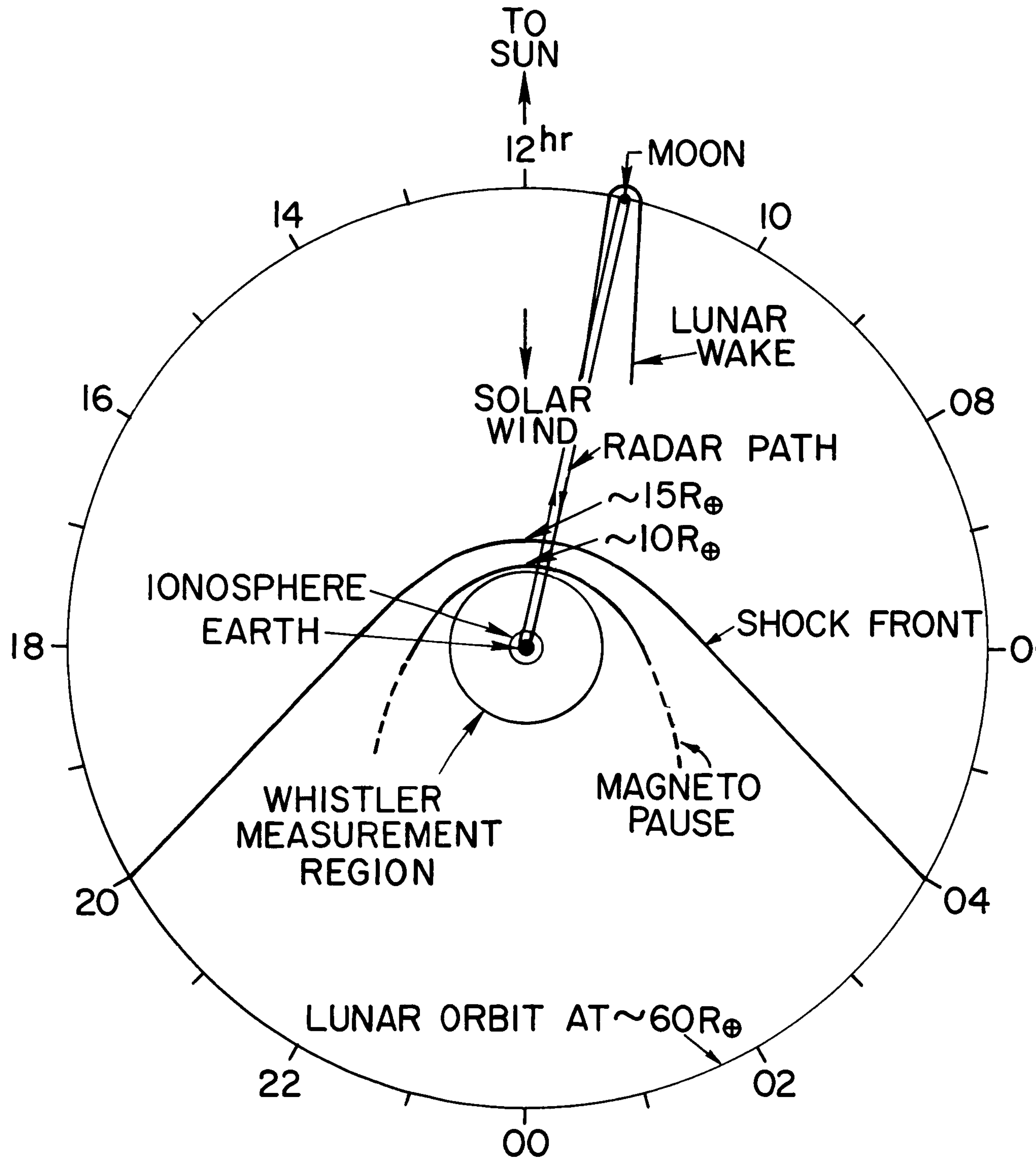


Fig. 1. ILLUSTRATION OF VARIOUS REGIONS OF THE CISLUNAR MEDIUM, AND AN EXAMPLE OF A LUNAR RADAR PATH

flow parameters. The radar path scanned this entire region several times during the experiment.

Experiment. The equipment and experimental procedures have been described in some detail by Howard et al [1964a,b,c; 1965]. We shall briefly discuss the experiment here. It involves the transmission of two harmonically-related frequencies at about 25 and 50 Mc using linear polarization. The time required for the complete cycle of operation for one echo is five seconds, i.e., 2.5 seconds of transmitting time followed by the same period for reception. The transmitting antennas were also used as receiving antennas for the Doppler frequency measurements. A 60-foot dish with a crossed-Yagi feed was used to measure the change of Faraday polarization angle at 50 Mc. The location of the dish is 800 meters from the transmitting antennas. The terminals of the crossed feed are connected to a goniometer rotating at 30 rpm, synchronized with the transmit and receive cycle. In addition to the measurement throughout a run of Faraday polarization angle, differential Faraday measurements were conducted at the beginning and/or end of each daily experiment. This additional measurement makes it possible to determine the total number of polarization rotations so as to provide a starting point or zero for the relative angle measurements. The experiment was conducted for one to three hours each day around local lunar transit time, while the moon was in the log-periodic array beam.

Equipment parameters are shown in the following table.

EQUIPMENT PARAMETERS

Transmitter power	50-kw average (50 Mc) 300-kw average (25 Mc)	
Frequency	49.802 Mc (50 Mc) 24.901 Mc (25 Mc)	
Pulse length	2.5-sec transmit 2.5-sec receive	
Transmitting antennas (linearly polarized)	150-foot dish (50 Mc) 48-element log-periodic array (25 Mc)	
Receiving antennas	150-foot dish (50 Mc) 48-element log-periodic array (25 Mc)	Doppler frequency
	60-foot dish with crossed-Yagi feed (50 Mc)	Faraday polarization
Receiver bandwidth	2 kc (50 Mc) 1 kc (25 Mc)	Doppler
	0.1 kc (50 Mc)	Faraday

Theory. The amount of rotation of polarization (Faraday rotation) in a magnetoionic medium can be written as [Howard et al, 1964b]:

$$\phi_F = \overline{\left(\frac{f_o{}^2 f_L}{2f^2}\right)} \; T_o \tag{1}$$

where ϕ_F is the number of Faraday rotations, f_L is the longitudinal gyro-frequency, f is the operation frequency, T_o is the free-space propagation time, f_o is the plasma frequency, $f_o \ll f$, and the bar denotes mean values along the path. The square of the plasma frequency is related to the electron density by the following relationship:

$$f_o{}^2 = 80.6 \; N$$

where N is the electron density. Since one Faraday rotation at 50 Mc corresponds to about 8×10^{15} electrons per square meter, which is about 1/10 of the normal ionospheric content, there will usually be an ambiguity concerning the total number of rotations when only the Faraday angle is measured. Evans [1957] showed that the ambiguity can be resolved by measuring the Faraday polarization at two closely spaced frequencies. The total number of Faraday rotations can thus be expressed as:

$$\phi_F = \frac{\Delta\phi_F}{2\Delta f} \; f \tag{2}$$

where Δf is the difference of two frequencies, and $\Delta\phi_F$ is the difference of measured polarization angles. The columnar electron content in the ionosphere I_F can be calculated from the number of Faraday rotations by use of the following expression:

$$I_F = \frac{1}{40.3} \frac{f^2 c}{f_L} \phi_F \tag{3}$$

where c is the speed of light in free space. The value of f_L is chosen at 400 km above the ground for the daytime measurements and about 500 km for the nighttime, so as to be representative of the whole ionosphere at these times of day [Yoh et al, 1965].

The time integral of the Doppler excess frequency (or dispersive Doppler frequency) is a measure of the electron content relative to an unknown zero point along the entire radar path [Howard et al, 1964a]. The relative electron content I_D can be expressed as:

$$I_D = \frac{1}{40.3} f c \phi_{DE} \tag{4}$$

where ϕ_{DE} is the time integral of the Doppler excess frequency.

Results. The averaged results of the measurements taken over the 5-month period are shown in Fig. 2, where relative electron contents are plotted as a function of local time. The dashed line is determined from the Faraday polarization measurements and the solid line from the Doppler excess frequency. The vertical bars denote measurement uncertainty. The Faraday polarization results I_F show the

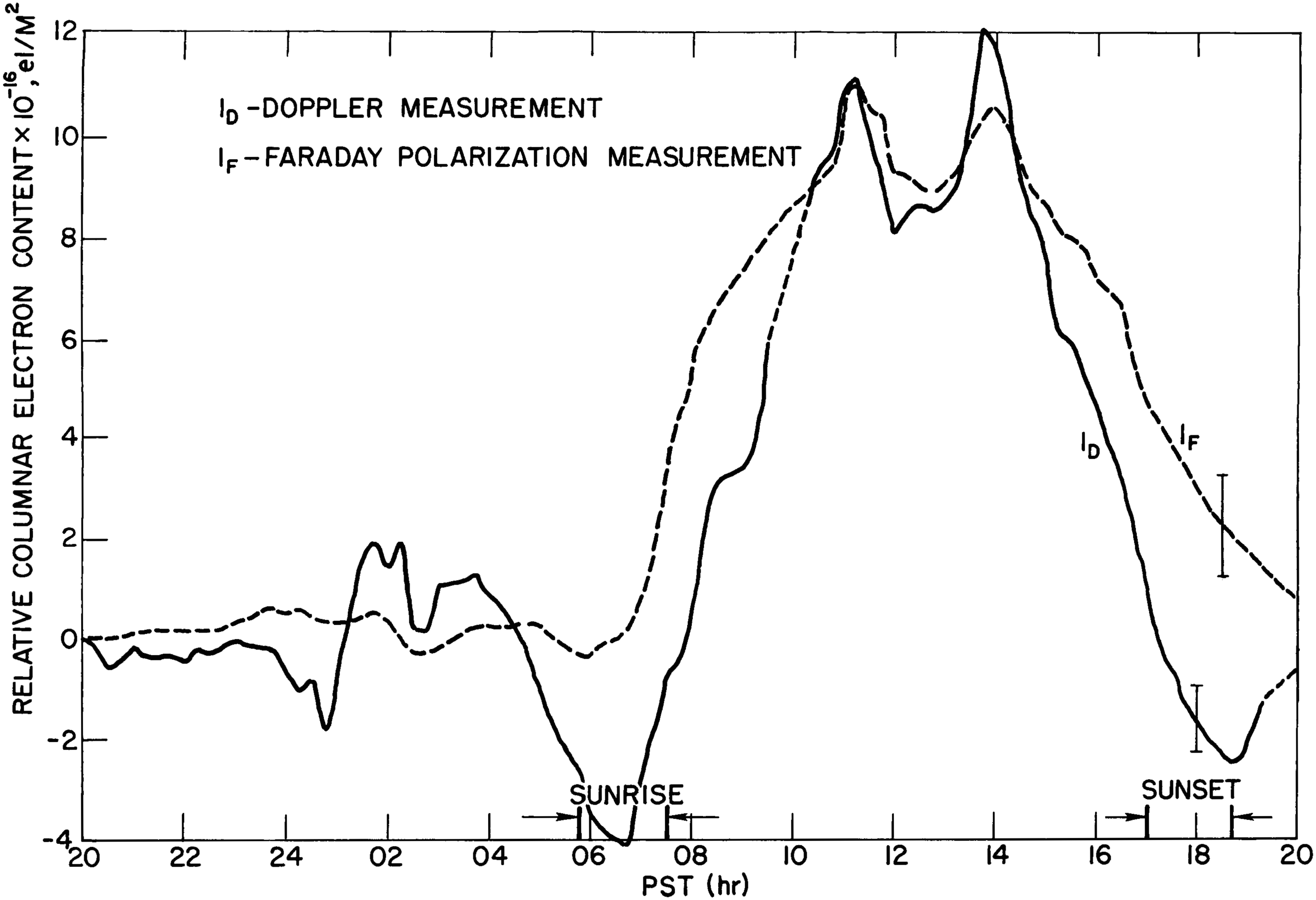
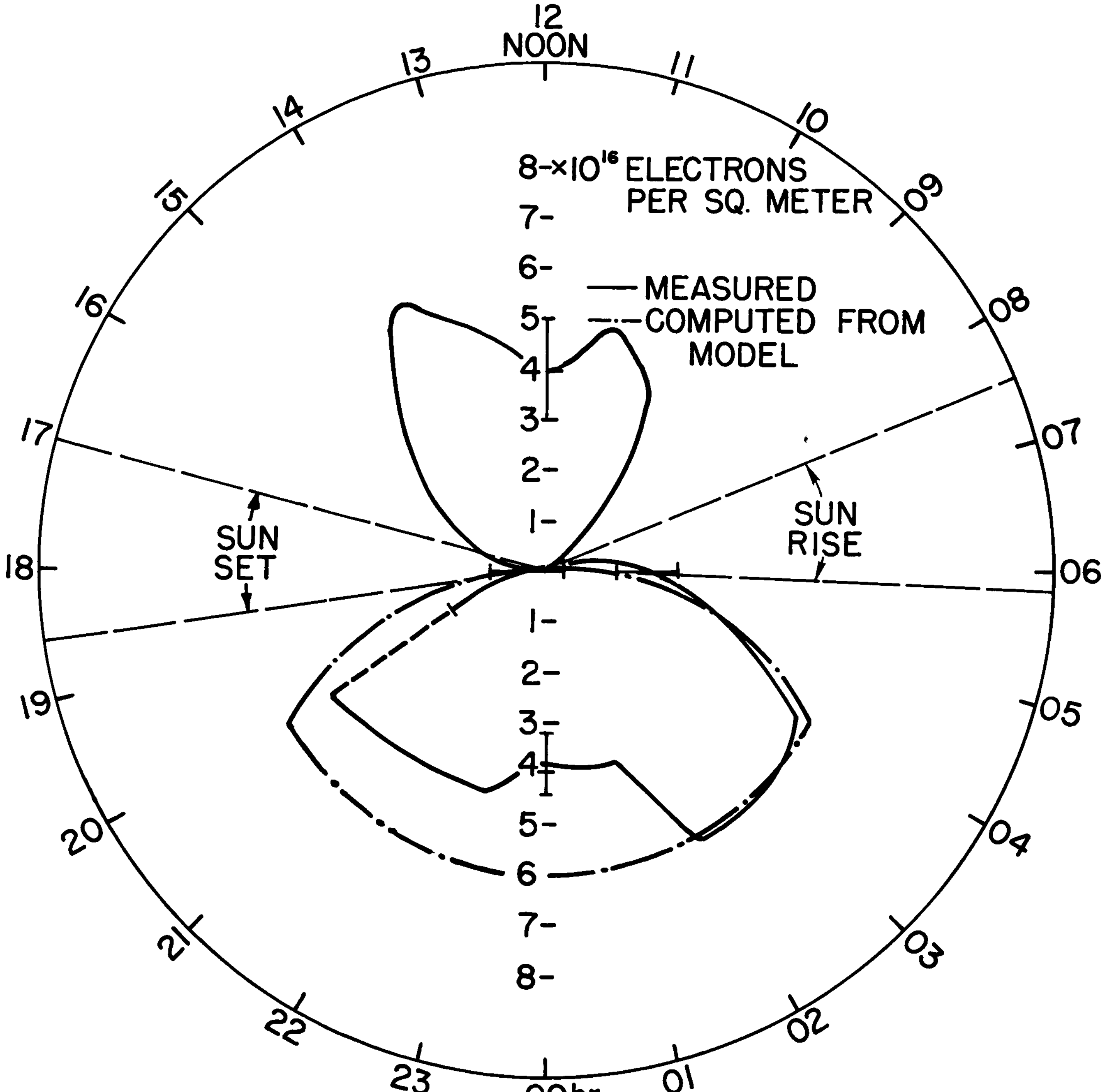


Fig. 2. DIURNAL CHANGES IN THE AVERAGE RELATIVE COLUMNAR ELECTRON CONTENT BETWEEN THE EARTH AND THE MOON, AS DETERMINED BY FARADAY POLARIZATION AND DISPERSIVE DOPPLER TECHNIQUES

average diurnal variation of the electron content in the ionosphere with the electron content increasing rapidly after sunrise and reaching its maximum value about noon. The content starts to decay in the early afternoon and continues to fall until after sunset. The nighttime value of electron content is nearly constant. Similar diurnal variations of the electron contents have been obtained at Stanford by measuring Faraday polarization of radio waves transmitted from a geostationary satellite [Garriott et al, 1965].

The variation of electron content measured by the Doppler excess method shows a different behavior from that based on Faraday polarization. The two most distinguishing features are the post-sunset increase of electron content and the predawn decrease. The difference of the curves for these two periods, I_D minus I_F, is plotted in polar coordinates in Fig. 3 (solid line). Since the Faraday method measures the electron content in the ionosphere and the integrated Doppler method measures the relative electron content along the entire radar path, Fig. 3 shows relative electron content beyond the ionosphere in the radial scale.

It should be noted that since echoes were obtained only near the time of lunar transit, the azimuthal scale in Fig. 3 may be interpreted either in terms of local time, or in terms of directions from the earth in (or near) the ecliptic plane relative to the earth-sun line. Thus, the 12-hour time represents the solar direction; the 24-hour time, the antisolar direction; and the 6-hour time, the direction of the earth's motion around the sun.



POLAR PLOT OF I_D-I_F VS LOCAL TIME

Fig. 3. DIURNAL AND DIRECTIONAL CHANGES IN THE AVERAGE DIFFERENCE BETWEEN THE COLUMNAR ELECTRON CONTENT DETERMINED FROM THE DOPPLER AND FARADAY MEASUREMENTS. Measurement results are shown by the solid line, while the broken line represents the results that would be obtained from the model discussed in the text.

Discussion. The electron content beyond the ionosphere shows a semi-diurnal variation. It is suggested that the variation of electron content on the daytime side is due to a diurnal exchange of the ionization between the upper ionosphere and lower magnetosphere [Yoh et al, 1965]. This subject will be discussed more fully in another publication.

We believe that the other main feature of Fig. 3, which shows large changes in integrated density during the post-sunset and pre-sunrise hours, is a directional effect related to the distribution of electron density in the magnetospheric wake. From these characteristics, a model is suggested having the following characteristics:

1. The cislunar electron density beyond the ionosphere in the anti-solar quadrant is greater by about 200 cm^{-3} than the solar-wind electron density.
2. The boundary of the discontinuity in density extends at least to the orbit of the moon.
3. This boundary is an extension of the measured magnetospheric shock front, and it intersects the lunar orbit at about 120^{o} from the earth-sun line (at 20 hours and 04 hours in Fig. 3).

Figure 4 shows the proposed boundary (solid line). The open circles joined by dotted lines are the shock wave and magnetopause boundaries measured by IMP-I [Ness et al, 1964].

The radar results are explained as follows. The pre-dawn decrease of integrated electron density beyond the ionosphere is

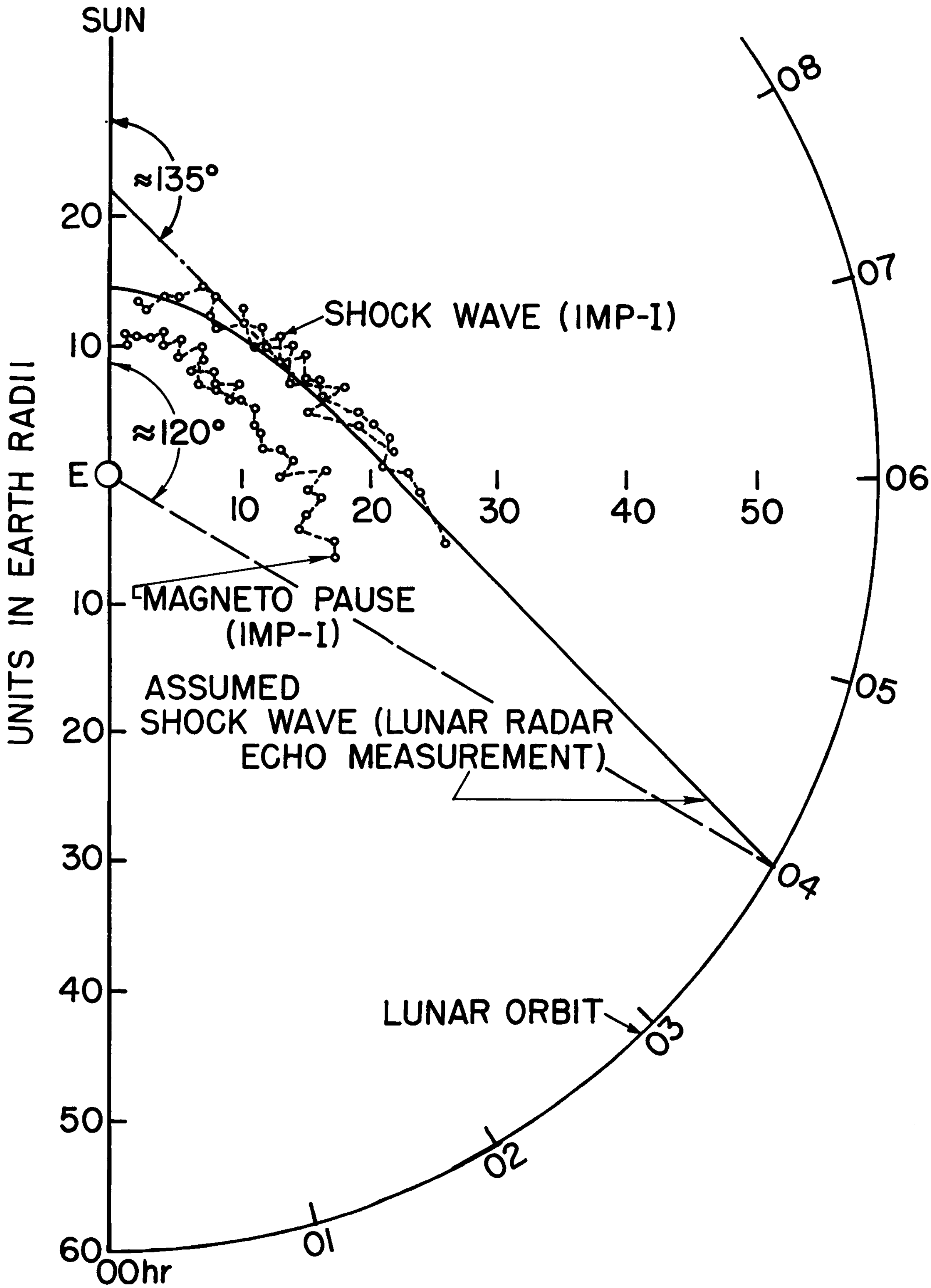


Fig. 4. SIMPLIFIED MODEL OF THE EARTH'S MAGNETOSPHERIC WAKE USED TO EXPLAIN THE NIGHTTIME RADAR RESULTS

due to the fact that the moon is moving toward the solar direction and, thus, the radar path length in the high density region is progressively shortened. Hence a decrease of the cislunar electron content is observed. The post-sunset increase is due to the moon moving toward the anti-solar direction. The part of the total radar path in the high density regions is lengthened so that the total electron content increases.

A computed relative electron content from the above model is plotted in Fig. 3 (dot and dash line) for comparison with the observations. While there may be other features in the data, such as a possible density reduction in the center of the wake, it appears that the principal features of the measurements are explained by this simple model.

Figure 4 shows that the boundary of the proposed model is a straight-line extrapolation of the measured shock wave boundary. At the limits set by the orbit of IMP-I, there is no indication that the shock front is curving back around the earth, as has been proposed in some models.

The low-energy,charged-particle measurements on IMP-I indicate a decrease in density as the satellite crosses the shock front from the post-shock regions to the pre-shock regions. The difference in density is from a few to over a hundred particles per cubic centimeter. The various instruments, however, are sensitive to different energy levels. It appears that the retarding potential analyzer can best be used for comparison purposes, since this instrument includes electrons at thermal energies (0 - 5 ev). It should be noted that radar measurements are sensitive to all non-relativistic electrons. Preliminary results for the retarding potential analyzer on the first out-bound orbit, as reported by Serbu [1965], imply an electron density of about 200 cm^{-3} inside the shock front, with no measurable electrons in this low energy range outside the shock front. Figure 5 shows the electron density calculated from the retarding potential analyzer results, assuming an isotropic distribution of directions and a mean energy of 1.75 ev (as measured at 9 earth radii) extending from about 5 to 16 earth radii.

Theoretical expectations for the ratio of particle densities on the two sides of the shock front are about 4 to 1 [Kellogg, 1962]. If one accepts the solar wind density in the preshock region as being about 10 cm^{-3}, then the density in the postshock region should be no more than 40 cm^{-3}. Thus, the measured values of the electron density in this region are much too large to agree with the theory. It is believed that the thickness of the shock front is of the order of a few kilometers [Parker, 1959]. However, the thickness of the measured magnetosheath between the shock and the magnetopause is of the order of tens of thousands of kilometers. Whether the density of the solar wind is much larger than the present accepted value, or the 4 to 1 ratio of density applies only to a small region at the shock front, needs further study and measurement.

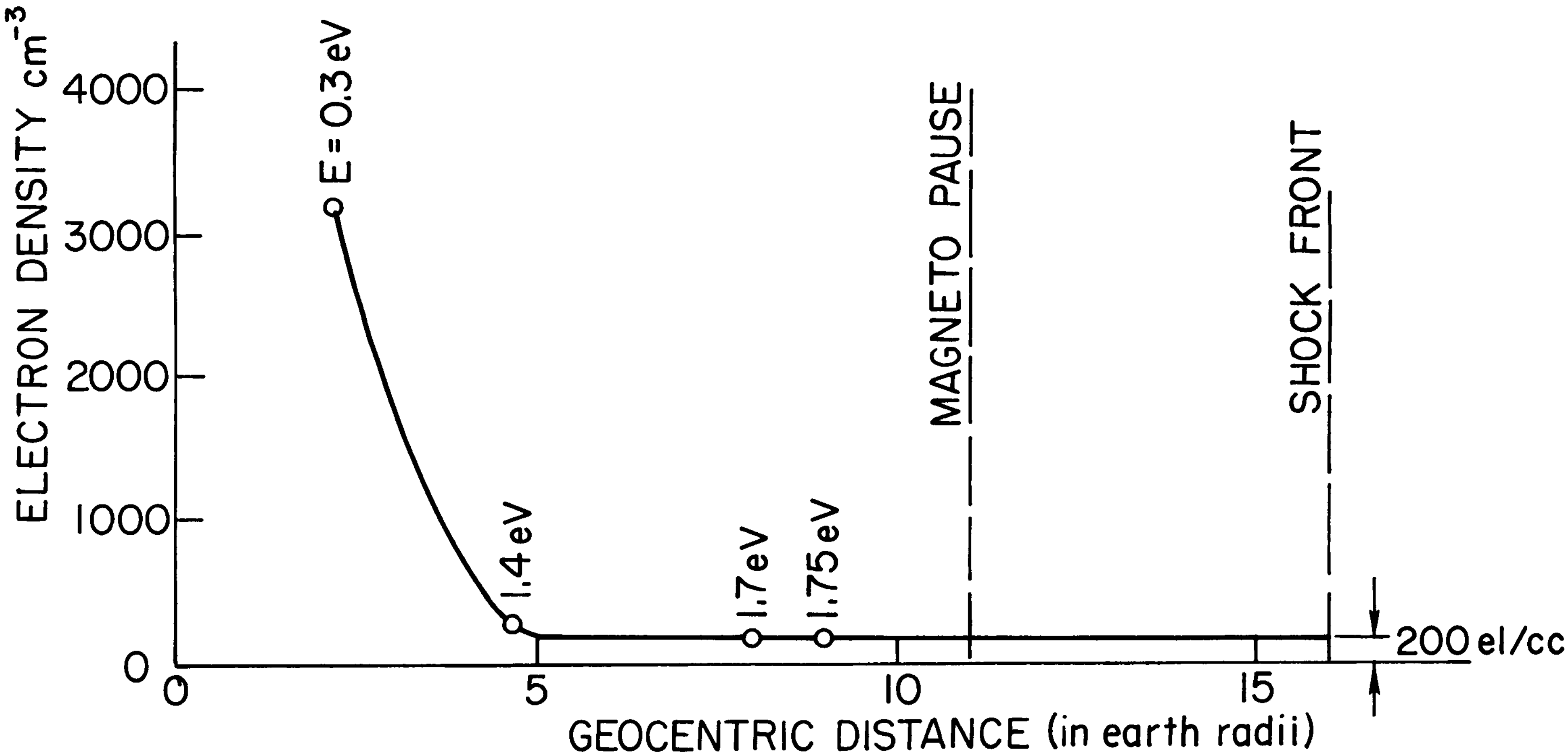


Fig. 5. THE LOW-ENERGY ELECTRON DENSITY DISTRIBUTION CALCULATED FROM THE FLUX AND ENERGY DISTRIBUTIONS MEASURED BY THE RETARDING POTENTIAL ANALYZER ON IMP-I

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